POTENTIAL AND LIMITATION OF DIRECT SENSOR ORIENTATION

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ABSTRACT

Based on combined use of an inertial measurement unit (IMU) and GPS, sensor orientations can be determined directly. Problems are included in the determination of the misalignment between the camera and the IMU, the long and short term stability of the physical connection of the IMU to the camera lens cone, the separation of the GPS-shifts from the misalignment and the reliability of the sensor orientations. In addition, the focal length has to be checked under flight conditions if different flying heights above ground are used.

The misalignment of the IMU from the camera axis can only be determined with sufficient accuracy by a reference flight strip flown in opposite directions and controlled with a standard bundle block adjustment. But also under this condition, some limitations are caused by the very high correlation of the sensor orientations, especially for normal or even smaller angle images.

For an operational project the sensor orientations of approximately 3000 photos, flown at different days, have been determined by IMU + GPS. The misalignment was determined every day by means of a small reference strip, flown before and after the images of the main block.

Limited, but still significant differences of the misalignment occurred. A check of the orientations against ground coordinates with 252 photos measured manually and 460 photos used in an automatic aero triangulation has shown sufficient results. Nevertheless larger discrepancies in the heading (kappa) have been shown – this also may be caused by the limited stability of the IMU mount in relation to the lens cone of the used LMK 2000. The lens cone is fixed only by one pin to the camera body. Also the other cameras do have similar mechanical problems.

In the case of Kodak DCS images, supported by IMU and GPS, a component calibration (misalignment and GPS shift) was not possible because of the very small view angle. After a general shift of the GPS-data, these values have been fixed to allow a sufficient system calibration. For the resulting ground accuracy a separation of the different error sources was not necessary.

A general problem of the directly determined sensor orientations is the missing reliability. Even simple errors like in the image numbers can only be seen by a model setup or the matching of created orthophotos. The model setup often is disturbed by not acceptable y-parallaxes. This can be solved by a combined bundle block adjustment. Based on the precise approximate image orientations an automatic aero triangulation can be handled much more easy, so the additional effort is limited.

1 INTRODUCTION

The image orientation for photogrammetric data acquisition is a very important, but time consuming procedure. With a block adjustment, the number of required control points has been reduced drastically. The next step was the combined bundle block adjustment with projection center coordinates determined by relative kinematic GPS-positioning. In the case of a real block structure, attitude data are not required, they can be determined by the combined block adjustment with GPS-data (figure 1), if at least 2 parallel flight strips are available. The flight strips

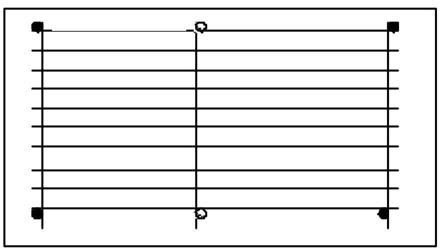


Figure 1: block configuration for combined adjustment with GPS – crossing flight strips every 20 – 30 base length or control points

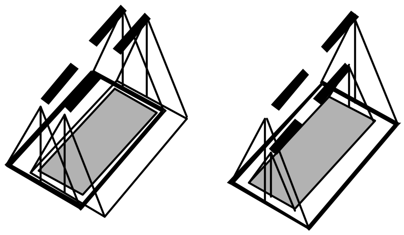


Figure 2: block configuration of linear objects – IMU-data not required

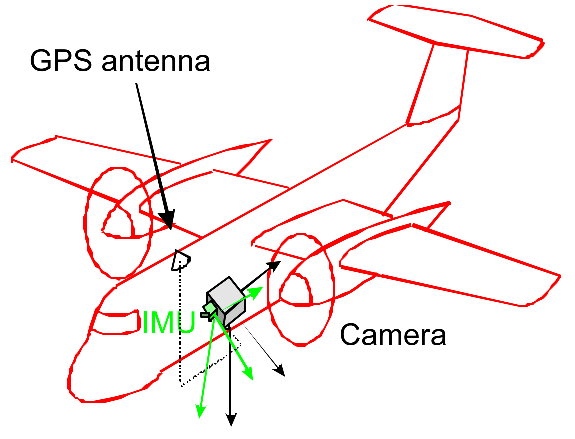


Figure 3: relation GPS-antenna and IMU to the camera – offset and misalignment

may be located one beside the other or even with a vertical displacement of the flight lines (figure 2). The classical location of one flight axis beside the other has the advantage of the same photo scale, this makes the determination of tie points more easy. Only for a single flight strip or a combination of single flight strips, attitude data are required in addition to GPS-coordinates of the projection centers if no control points are available, because of the problem with the lateral tilt. But even for a real block structure, the combined use of GPS and IMU in the aircraft has some advantages. In a combined computation of the IMU- and GPS-data by a Kalman filtering, GPS cycle slips can be determined and so the problem of shifts and drifts of the GPS-data, different from flight strip to flight strip can be solved. In such a case, the crossing flight strips are not directly required, but they do have the advantage of a better control of the block geometry and they are avoiding also problems of a not accurate lateral tilt of long flight strips.

If not a very high accuracy is required, with the combined use of GPS and IMU the sensor orientation can be determined directly also without knowledge of image coordinates. As result of the Kalman filtering we will get roll, pitch and yaw of the IMU and the coordinates of the GPS antenna. The axis of the IMU will not be parallel to the photogrammetric camera – this boresight misalignment has to be determined by means of a reference bundle block adjustment. The stability of the boresight misalignment has to be checked - the photogrammetric cameras have not been constructed for the attachment of the IMU with the sufficient stability. The antenna offset from the camera projection center to the antenna and to the IMU has to be determined. It is not sufficient to use the orientation information of the IMU for the reduction of the GPS-position from the antenna to the projection center because usually the camera is rotated within the aircraft for the aircraft drift correction. Only if the antenna is located exactly above the camera, this can be avoided. Otherwise the rotation of the camera against the aircraft has to be recorded.

2 PROJECTS

In cooperation with BSF (Berliner Spezialflug Luftbild und Vermessungen GmbH, Diepensee) and IGI Hilchenbach a larger block has been handled. The location of 2856 images taken in 4 flight days are shown in figure 4. Every day the misalignment and systematic GPS-position-errors have been determined before and after the flight over the main area by means of a small reference area located north of the block. In addition, for checking purposes, a sub-block with 252 images and another with 460 images have been determined by combined block adjustment without IMU, so independent reference data are available.

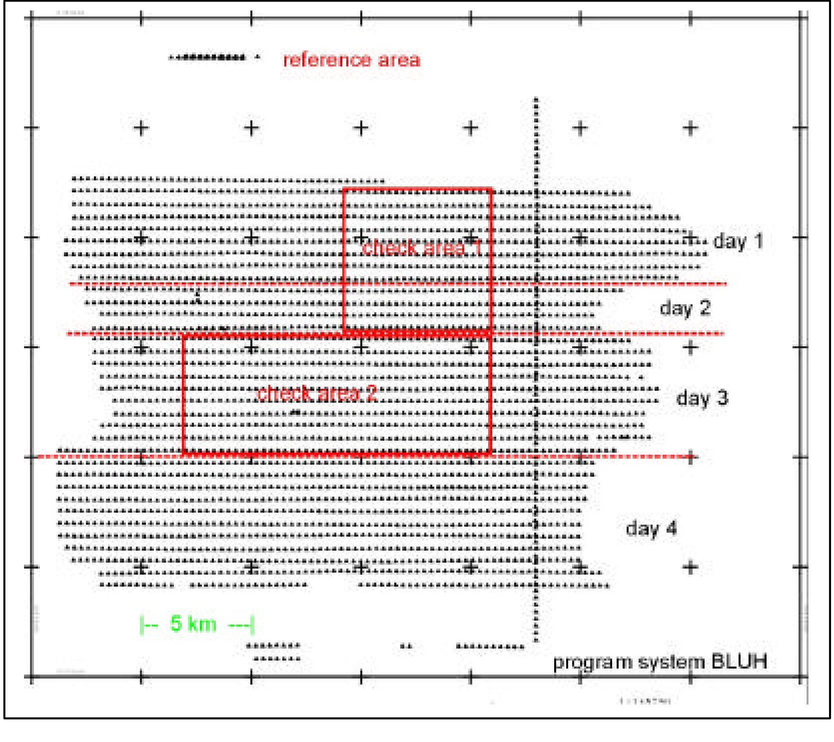


Figure 4: configuration of the project area

The inertial measurement unit LCR88 was mounted on top of a LMK 2000. An additional IMU, fixed to the aircraft, has been used for the reduction of the antenna position to the projection center. The flying height of approximately 1090m above terrain corresponds with the focal length of 305mm to a photo scale 1 : 3500. The direct orientation of a normal angle camera is more difficult than the handling of a wide angle camera, approximately the double accuracy is required for the attitude data and the determination of the misalignment is

influenced by the more strong correlation of the orientation unknowns. The large photo scale was required for the identification of the mapping objects and not for the accuracy. An accuracy of +/-1m in X and Y was required for the ground points corresponding to 285µm. But for a stereoscopic view, the y-parallax should not exceed 30µm.
Another small block has been processed in cooperation with the University of Applied Sciences, Bochum, Germany (Bäumker et al 1999). With a self developed, fast reacting stabilized platform for carrying a digital camera Kodak 520, the sensor orientation has been determined and so the camera was very close to a nadir view.

3 PREPARATION OF THE INERTIAL DATA

The IMU is determining roll, pitch and yaw. Also after correction by the boresight misalignment such rotations cannot be used directly for the setup in photogrammetric work stations. The primary rotation yaw is related to geographic North instead of the grid North used in photogrammetry. With the program IMUPRE of the Hannover program system BLUH the IMU-attitude data have been converted into the usual photo orientations respecting the convergence of meridians, the different rotation definition and the dimension of the attitude data (grads instead of degrees). By a comparison of the photo orientations of the reference blocks with the orientations determined by means of GPS and IMU, the relation of the axis between the photogrammetric camera and the IMU has been determined as well as systematic differences of the GPS-positions. By linear time depending interpolation, based on the results of the reference strips flown before and after the flight over the main area, the photo orientations of the images in the main area have been improved. The improvement of the attitude data was done in the pitch, roll and yaw-system, corresponding to the relation of the axes.
The photo orientation determined by bundle block adjustment is not free of errors, especially in the case of a small view angle the orientation elements do have strong correlation's. Especially the correlation of X0 and Y0 to phi and omega is in the range of 0.995, that means, shifts of the GPS-data and angular misalignment cannot be separated totally (Jacobsen 1999). The separation of the components can be improved by a flight over the reference area in opposite direction, but this was not done.
In general a problem of the separation will only have a negative influence if the flight over the main block area will be made under different conditions. In the case of the same image scale and same flight direction, a separation of the components is not required. For the fast reacting platform, equipped with a Kodak DCS 520, the view angle was only 24° x 34.7°, causing a correlation of the orientation elements computed by resection up to 0.999. It was not possible to separate shifts in X0 and Y0 from roll and pitch. By this reason, after an approximate shift of the GPS-data, the projection center coordinates X0 and Y0 have been fixed for the determination of phi and omega.

	boresight misalignment		
	roll [grads]	pitch [grads]	yaw [grads]
systematic differences day 1	-.445	-.469	.534
“ day 2	-.454	-.462	.571
“ day 3	-.463	-.462	.645
“ day 4	-.477	-.471	.595
	mean square differences		
without systematic differences day 1	.039	.012	.044
“ day 2	.029	.016	.049
“ day 3	.042	.021	.117
“ day 4	.034	.015	.091
after linear fitting *day 1*	*.025*	*.009*	*.007*
“ day 2	*.021*	*.009*	*.010*
“ day 3	*.026*	*.014*	*.012*
“ day 4	*.017*	*.016*	*.008*
after fitting by t^3 day 1	.011	.009	.007
“ day 2	.021	.009	.010
“ day 3	.018	.015	.011
“ day 4	.018	.006	.005

Table 1: differences of the attitude data IMU – controlled bundle block adjustment (reference flight strips)

In table 1 the attitude differences between the controlled bundle block adjustment and the IMU-data in the reference area are shown. The misalignment in roll and pitch is constant over the 4 days within the standard deviation. This is not the case for yaw. A significant change of the yaw between the flight over the reference flight strip before the main area to after this happened (much smaller values “after linear fitting”). If this change is a linear function of the time, it can be respected in the determination of the image orientation based on the IMU-data. The determination of the misalignment and the bundle block adjustments have been made with the Hannover program system for bundle block adjustment BLUH. In the module for the transformation of the IMU-data to photogrammetric orientation, the misalignment has been respected as linear function of the time. The same was done with the GPS-coordinates of the projection centers. The constant discrepancies of the GPS-data have been in the range of 1m. After the correction of the systematic discrepancies, the mean square differences are in the range of +/- 0.2 – 0.5m for SX and SY and +/-0.2m for the height. The height is not influenced by strong correlation, so this is a realistic figure for the quality of the GPS-data.

4 ANALYSIS OF THE ACHIEVED RESULTS

In both check areas, marked in figure 4, an analysis of the of the direct determined sensor orientation was possible by bundle block adjustment. The first area includes 252 images measured manually, the second 460 images with image coordinates determined by automatic aero triangulation.

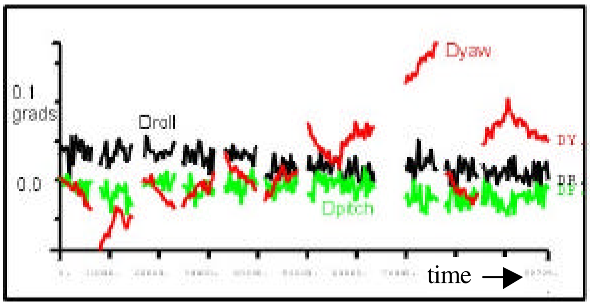


figure 5: discrepancies at attitude data check area 1

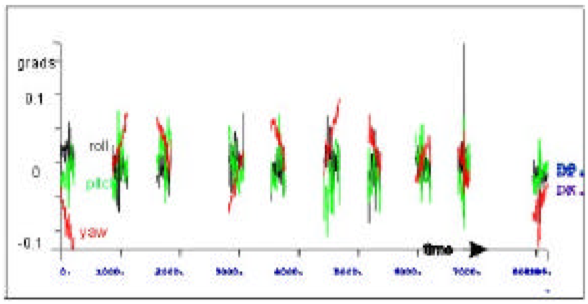


figure 6: discrepancies at attitude data check area 2

	pitch	roll	yaw	pitch	roll	yaw
	check area 1			check area 2		
absolute	0.028	0.020	0.059	0.023	0.031	0.049
without shift	0.010	0.010	0.013	0.021	0.025	0.012
linear fitting	0.010	0.010	0.007	0.022	0.023	0.009

Table 2: discrepancies of the attitude data [grads] corrected IMU – bundle block adjustment

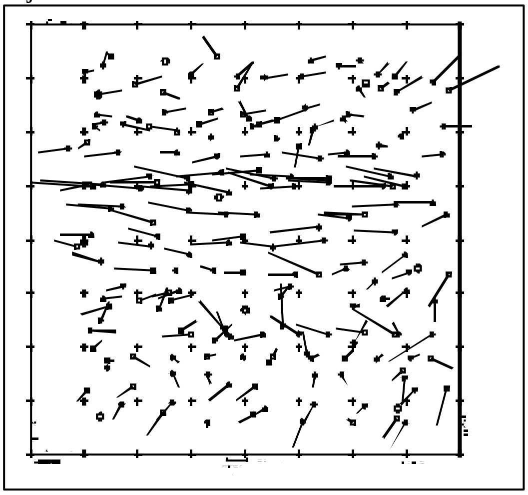
	X0 [m]	Y0 [m]	Z0 [m]
absolute	0.21	0.22	0.64
without shift errors	0.15	0.13	0.05
linear fitting	0.16	0.14	0.05

Table 3: discrepancies of the projection centers corrected GPS-data - bundle block adjustment

Figure 5 and 6 as well as table 2 are showing the discrepancies of the attitude data determined by direct sensor orientation (IMU improved by misalignment) against the results of the bundle block adjustment. Systematic errors are obvious, by this reason the systematic components are removed individually flight strip by flight strip - this represents the results shown under 'without shift' and 'linear fitting'. There is no general difference between both areas. The result of the linear fitting is close to the relative accuracy (one orientation against the orientation of the neighbored image) which is important for the model setup.
The photo orientations determined by bundle block adjustment based on control points are not free of errors. The adjustment is giving following mean square standard deviations as mean value of all:
Sphi=0.0017 grads, Somega=0.0017 grads, Skappa=0.00042 grads, SX0=0.033m, SY0=0.034m, SZ0=0.015m.

The discrepancies at the projection center coordinates between the GPS-data corrected by the reference blocks and the results of the bundle block adjustment of the check area (table 3) are corresponding to the discrepancies determined by the combined block adjustment itself. Especially the discrepancies in Z0 are obvious, but this has to be seen also in relation to the height-to-base-relation of 3.2 for the used normal angle camera.

More important than the discrepancy of the individual orientation components are the discrepancies at the ground coordinates determined with the improved photo orientations. Because of the strong correlation of the orientation elements it is not possible to calculate the accuracy of the ground coordinates just by simple error propagation. With the photo coordinates and the photo orientations determined by GPS and IMU a combined intersection has been computed and the resulting ground coordinates have been compared with the results of the controlled bundle block adjustment.



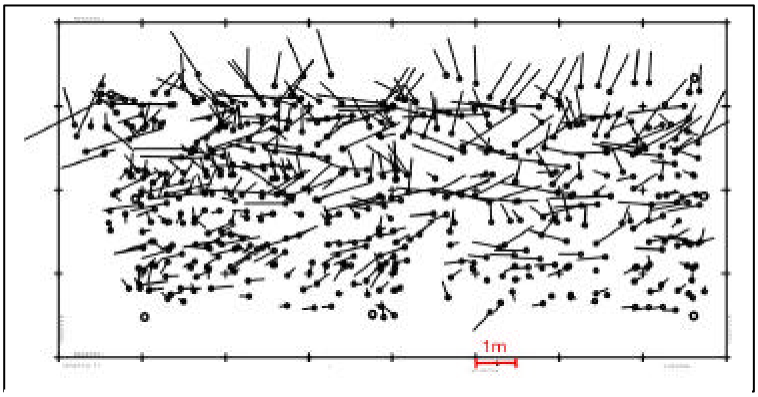
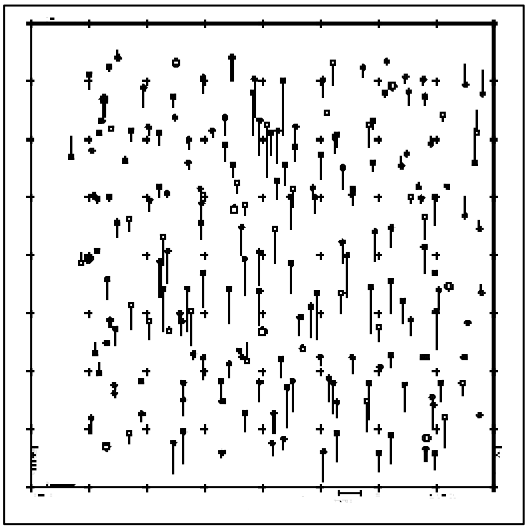


Figure 7: discrepancies at ground coordinates X, Y left: check area 1, above: check area 2 (check area 1: 10% of 1886 points, check area 2: 1% of the 51793 points are shown)



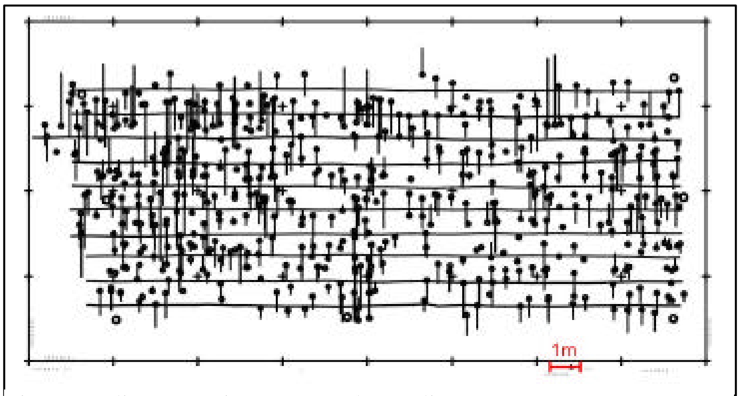


Figure 8: discrepancies at ground coordinates Z
left: check area 1
above: check area 2

The results of both check area are similar. The first check area includes in total 1886 ground points, the second because of the automatic aero triangulation, 51793 points. Local systematic errors can be seen in the same way.

	X [m]	Y [m]	Z [m]	X [m]	Y [m]	Z [m]
	check area 1			check area 2		
RMS of absolute differences	0.42	0.18	0.85	0.34	0.26	1.05
systematic differences	-0.18	0.01	-0.59	0.08	-0.12	0.95
RMS without systematic differences	0.38	0.18	0.61	0.33	0.24	0.46

Table 4: discrepancies at the ground coordinates

The lower accuracy in Z can be explained by the normal angle camera, that means the height-to-base-relation is 3.2 (in the case of a wide angle camera 1.6), so the accuracy in Z should be 3.2 times the accuracy in X or Y. The required accuracy of 1m in X and Y has been reached.

The small block, flown with the fast reacting platform and the digital camera Kodak DCS 520 could be checked completely by control points. A bundle block adjustment without IMU-data is resulting in a sigma0 of 0.5pixel or 0.35m on the ground. As mentioned before, it was not possible to separate the systematic GPS-errors from the misalignment, so it was necessary to fix the X0- and Y0-values. This resulted finally in a horizontal accuracy in the range of 5m, sufficient for the project.

5 MODEL SETUP

The absolute accuracy is only one result. For the model setup, the relative accuracy, represented by the y-parallax, is more important because a large y-parallax is preventing the stereoscopic view. The relative accuracy of the ground coordinates computed by common intersection - the accuracy of a point in relation to another point in the neighborhood - for distances up to 500m is RSX = 0.19m, RSY = 0.10m and RSZ = 0.36m. This corresponds to a mean square influence of 42µm which is exceeding the limit of the tolerance for the model set up, but the relative accuracy is only indicating and does not say directly something about the y-parallax.
Also the neighbored orientation values are correlated, for phi the correlation of neighbored orientations is r = 0.81, for omega r = 0.57. This leads to a relative accuracy of RSphi = 0.011 grads, RSomega = 0.010 grads and RSkappa = 0.005 grads. For the relative orientation especially omega is important. Just the value for omega is reaching 0.010 grads • focal length 305mm = 53µm, exceeding the tolerance limit of 30µm for the model setup.
In the check areas the y-parallaxes have been checked by intersections based on the direct determined sensor orientations and the available image coordinates. The mean square value of the y-parallaxes for all intersections is 56µm, that means it is too large for the model setup. 64% of the models are exceeding a mean square y-parallax of 30µm, which can be used as a tolerance limit, 36% are exceeding 50µm and 6% are exceeding 100µm. This shows the problems connected with this data set. If it is compared with other published data sets, it has to be respected that a normal angle camera has been used. The influence of the attitude data to a wide angle camera is only half of this.
Figure 9 and 10 are showing on the left hand side the y-parallaxes of the intersection of 2 models based on the direct determined sensor orientation. The dominating constant shift is obvious - this is typical for all models. By this reason

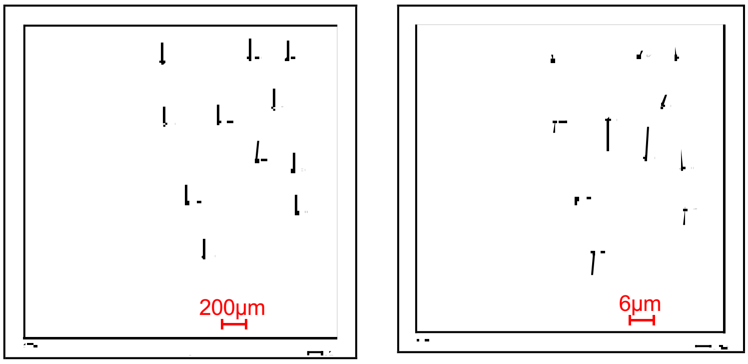


Figure 9: y-parallaxes model 188/189
(manual measurement)
left hand: intersection based on direct determined sensor orientation
mean square y-parallax: 141 µm
right hand: y-parallax after shift of one image in y-direction
mean square difference: 4 µm

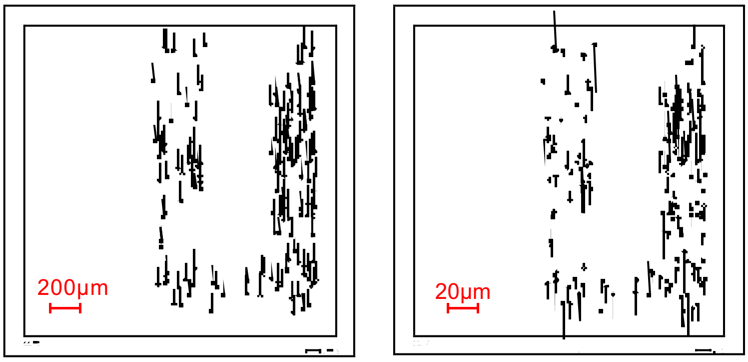


Figure 10: y-parallaxes model 11050/11051
(automatic aero triangulation)
left hand: intersection based on direct determined sensor orientation
mean square y-parallax: 132 µm
right hand: y-parallax after shift of one image in y-direction
mean square difference: 15 µm

the mean shift has been removed, leading to much better results. The mean square value of the y-parallaxes for all intersections is reduced by this from 56µm to 14µm. No mean square shifted y-parallax for a model is exceeding 30µm and only 33% are exceeding 20µm. That means, if the models shall be set up, a simple method for a y-shift of one image against the other can solve the problem. The direct determined sensor orientation have to be transferred to the different photogrammetric workstations, which is possible by the different transfer programs included in program system BLUH. Based on measured y-parallaxes only the projection centers of the transfer parameters have to be changed. Of course it is better to include this as a function in the workstation software, but this usually has to be made by the different photogrammetric software companies.

6 CONCLUSIONS

The determination of the boresight misalignment includes especially for normal and small angle images the problem of a limited separation of the different error components. A flight in opposite direction over a reference area or just strip should be done to enable a sufficient separation of the misalignment in roll and pitch from the constant GPS-shifts in X and Y-direction. If different flying altitudes should be used, also the reference area should be flown under similar conditions to allow a separation of GPS-shifts in Z-direction from discrepancies of the focal length which can be caused just by the temperature conditions of the photo flight. For a block flown with a DCS 520 with small angle lenses, a separation of influences from GPS and misalignment was not possible, so the X- and Y-coordinates of the projection centers had to be fixed to the GPS-data for the determination of the reference orientations.
Over the 4 days of photo flight, the change of the misalignment in roll and pitch was within the standard deviations, only the yaw has changed significant, also during one day. This requires a check of the misalignment every day if the same photogrammetric camera will be used. It may be different for other camera types.
Ground coordinates computed by common intersection based on the direct determined camera orientations of a normal angle camera and image coordinates in a scale 1 : 3500 have had mean square discrepancies in X and Y in the range of 30cm and for Z 0.95m, sufficient for the project. Problems are existing with the setup of stereo models. The mean square y-parallaxes are 56µm, even for 6% of the models more than 100µm. The dominating part of the y-parallaxes is a constant shift. If this will be removed, the remaining mean square values are reduced to 14µm and in no model 30µm have been exceeded.
Another problem is the missing reliability. Even simple errors of the image numbers can be detected only by a model setup or the matching of orthophotos. A combined block adjustment is solving this problems and is avoiding a disturbing size of y-parallaxes.

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